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SOVIET DEVELOPMENT OF FLASH X-RAY MACHINES

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PREFACE

This Report has been prepared under a continuing program, sponsored by the Defense Advanced Research Projects Agency, which undertakes the systematic coverage of selected subjects of Soviet scientific and technological literature.

Current research of leading Soviet physicists is of considerable interest in shedding light on significant R&D areas being explored in the USSR, on their topical priorities in research efforts, and perhaps to some extent on their research goals. An insight into these factors is enhanced if one examines a given activity in terms of an orderly progression of research reports spanning an appreciable period of time, the extent and consistency of teamwork within the activity, and its relation to other, similar efforts.

The material on Soviet development of high-power flash X-ray machines was prepared from Soviet and U.S. open-source publications covering the period from 1968 to 1973, and represents a significant aspect of the continuing study of high current beams developed in the Soviet Union.

The information here assembled conveys our recent knowledge of the Soviet state of the art in this field, and thus is intended to contribute to the work of American researchers in government-supported programs.

SUMMARY

The designers of the RIUS electron accelerator series are developing new machines with pressurized water as the dielectric. The physical properties of water make it superior in this application to conventional materials, such as oil, offering the opportunity to achieve higher power levels and pulse repetition rates. The breakdown strength of water was found to be particularly sensitive to its pressure. A prototype accelerator system of a moderate size was built in which water resistivity reached nearly 2×10^7 ohm-cm at 100 atm; it is capable of delivering 5×10^{11} W for a stored energy of 30 kJ. Megavolt accelerators were also built using unpressurized water which was found to be on par with oil in terms of the electric strength. Flash X-ray machines in which X-ray excitation occurs at near atmospheric pressures are being considered.

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SOVIET DEVELOPMENT OF FLASH X-RAY MACHINES

The subject of high-power electron accelerators has in recent years engaged several groups of prominent Soviet researchers, each of which deals with specialized aspects of the problem, such as high-voltage energy sources, field emissions technology, and electron-ion interaction. The activities and achievements of most of these groups will be the subject of a series of future reports based on the fairly large body of retrospective and current Soviet open-source literature in this field. The present Report deals with the group responsible for developing the designs of flash X-ray machines. As stated by their authors, these machines are intended for the study of radiation resistance of materials, high-speed phenomena, radiobiological effects, etc. The technology involved is, of course, also directly applicable to the generation of high-intensity relativistic electron beams for plasma heating, coherent acceleration of ions, or stimulation of artificial auroras.

The Soviet group working specifically on flash X-ray machines includes Ye. A. Abramyan, O. P. Pecherskiy, V. A. Tsukerman, and K. F. Zelenskiy, who appear as the leaders among a sizable number of authors. The existence and identity of the group itself is revealed through coauthorship and citation linkages involving most of its members, although in most cases an institutional affiliation is not given. Abramyan is associated with the Institute of Nuclear Physics, Siberian Department, Academy of Sciences, USSR, in one paper, and with the Institute of Theoretical and Applied Mechanics, Siberian Department, Academy of Sciences, USSR, in another. G. I. Budker, the well-known high-energy physicist noted for his work on opposed-beam accelerators, has been frequently cited as initiator and evaluator of some of the projects pursued by the group. There are also other research groups whose work is discussed in this paper; although they are not directly concerned with the flash X-ray applications, they have developed accelerators very similar to those of Abramyan.

In a review of flash X-ray machine development, Tsukerman [1] has outlined some principles and problems of design. The intensity of flash X-rays can be achieved by two methods: increasing the electron energy or increasing the current. Within the energy range of E = 2-6 MeV, the dose of a single flash in the direction of electron flow increases as $E^{3.4}$. The high value of the exponent of E is due to increased efficiency of electron transformation into X-ray quanta and decreased divergence of the X-ray beam at high accelerating voltages. In order to increase the electron current, it is necessary to reduce the source voltage impedance to a minimum. For this purpose, coaxial lines and reduced dimensions of the machine based on high-strength dielectrics are extensively used in the developments described by Tsukerman et al. [1].

Zelenskiy has noted that the large energies liberated at the anode cause considerable heating and increase the residual gas pressure in the accelerator tube after each discharge [2]. Therefore, such machines as a rule are built of removable sections that operate with continuous pumping at pressures of 10^{-6} torr and higher. This precludes the use of field-emission needle cathodes such as those developed for the Field Emission Corporation's systems, which can operate only under conditions of superhigh vacuum. With accelerating voltages of 3 to 10 megavolts and interelectrode gaps several centimeters long, the electric fields necessary to produce high-power field emission are obtained from cathodes whose radii of curvature are tenths of a millimeter. Field-emission cathodes may also have larger radii of curvature if many microtips are present on the cathode surface.

In high-power generators, the sources of high voltage can be capacitive Marx generators, pulse transformers, or electrostatic generators. A small section of a coaxial line or a capacitance charged by such sources is discharged across the accelerator tube via a discharge gap that increases the slope of the leading edge of the pulse up to 10^{14} to 10^{15} volts/sec [1].

These principles were employed in the series of machines developed by the Soviet group over several years. An early version of a flash X-ray machine built by Zelenskiy was driven by a Marx generator rated for 3.1 MV and storing 31 kJ. The X-ray tube produced a radiation dose of up to 5 rads at 1 m from the target in a pulse 0.3 μsec long for a current of 10 ka [2].

In 1968 Zelenskiy reported the completion of a 4-MV machine driven by two synchronous Marx generators connected in parallel and capable of storing 200 kJ at 5 MV. The two-electrode 4-MV pulsed X-ray tube is housed in a steel cylinder 0.8 m in internal diameter and 1.2 m long. The device can be operated with two different polarities of the high-voltage pulses. With a positive pulse, the anode of the tube is represented by a tungsten cone mounted at the end of a rod coincident with the axis of the tube. With a negative pulse, the anode is represented by a thin plate of a heavy metal, such as tungsten or tantalum, placed next to the output window of the tube. Under these conditions, the reduced distance between the source of X-rays and the specimen can insure especially high dosages. In operation of the device the amplitude of the discharge current varied from 30 to 60 ka. The length of the flash was 0.5 μsec. Radiation dose at a distance of 1 m from the X-ray target was initially 50 rads [3]. This was subsequently increased to 250 rads per pulse with improved electrode geometry [1]. At the distance of 2 to 3 cm from the target the dose was 120 krads. The thickness of lead that could be X-rayed 1 m from the target by single X-ray flash was 18 to 20 cm [3].

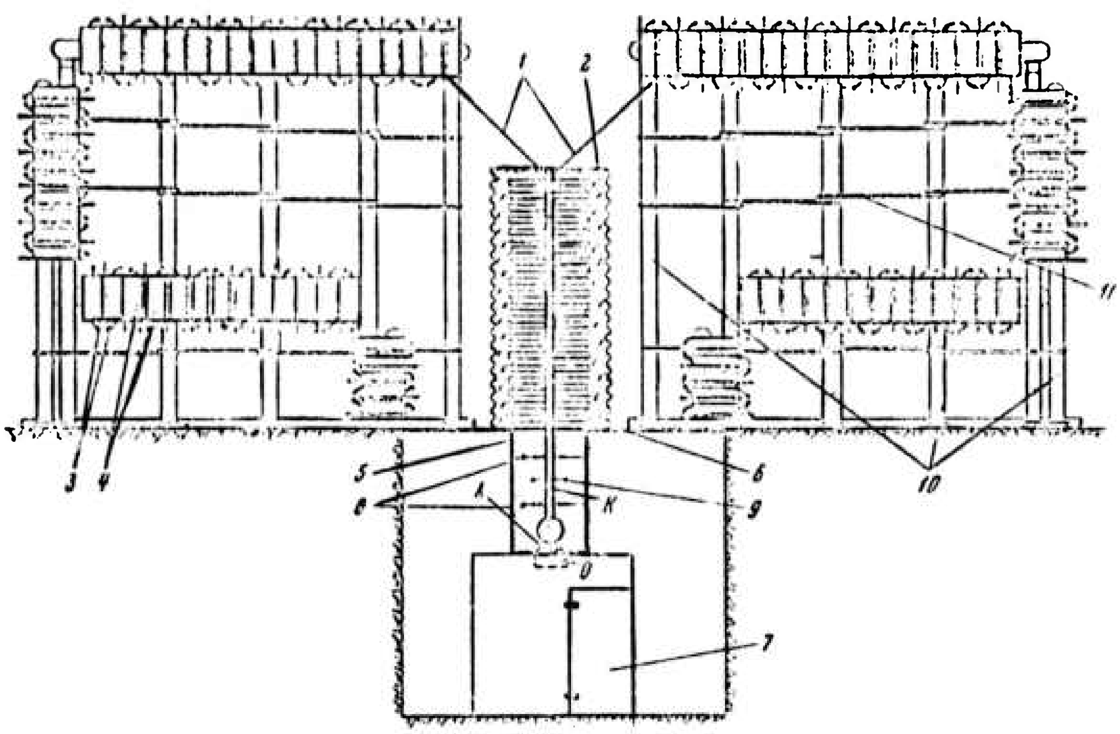
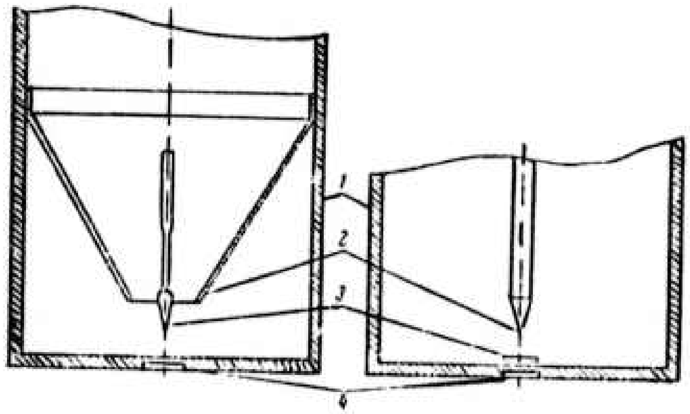


Fig. 1 -- Zelenskiy's 1968 flash X-ray machine [3]

A -- anode; K -- cathode; 0 -- specimen; 1 -- bus;
2 -- insulator; 3 -- spark gaps; 4 -- capacitor sections;
5 -- X-ray tube cylinder; 6 -- steel cover plate;
7 -- experimental station; 8 -- diaphragm; 9 -- disc;
10 -- insulator columns; 11 -- dielectric tie-rods.



a b

Fig. 2 -- X-ray tube details [3]

a -- electrode geometry for positive pulse; b -- electrode geometry for negative voltage pulse; 1 -- grounded tube cylinder; 2 -- cathode; 3 -- anode; 4 -- output window.

In 1969 Abramyan announced the RIUS-5 flash X-ray machine developed at the Institute of Nuclear Physics, Siberian Department, Academy of Sciences, USSR. Although it operated with a lower energy than Zelenskiy's machine, it had a shorter pulse. The high-voltage source was a Tesla transformer built into the X-ray tube housing rated at 5.4 kJ and 7 MV. The housing was a cylinder 180 cm in diameter, 550 cm long, filled with a mixture of 50 percent each of nitrogen and sulfur hexafluoride under a pressure of 15 atm. The RIUS-5 accelerator produces an electron beam of 4 MeV, 30 kA, and 40 nsec. The integrated dose is 2×10^4 rads per pulse in the plane of the window, and 10 rads per pulse 1 m from the target, sufficient to X-ray a lead specimen 16 cm thick 1 m from target in a single pulse.

The basic parameters of the accelerator are as follows: natural frequency of the primary and secondary circuits are 32 kHz, coupling coefficient is 0.47, maximum voltage reached is 7 MV, transformer ratio is 125. The pulse shaping gap between the line and the diode

employs trigatron ignition. The anode of the diode can be either a 0.5-1 mm Ta plate to generate X-rays, or a 50 μ, 80 mm in diameter Ti foil to release the electron beam into the atmosphere [1, 4, 5].

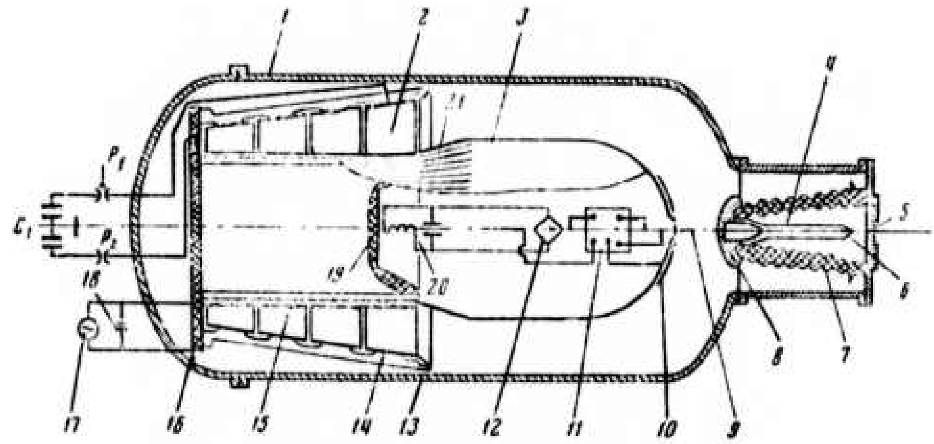


Fig. 3 -- The RIUS-5 flash X-ray machine [4, 5]

1 -- housing cylinder; 2 -- transformer primary; 3 -- line; 4 -- diode; 5 -- anode; 6 -- field emission cathode; 7 -- epoxy resin insulator; 8 -- hemispherical electrode; 9 -- gap; 10 -- voltage divider; 11 -- initiation synchronizer; 12 -- initiation circuit; 13 -- insulator; 14 -- support; 15 -- transformer secondary; 16 -- transformer insulator; 17 -- initiation oscillator; 18 -- oscillator gap; 19 -- secondary screen; 20 -- oscillating circuit.

A machine with output power levels similar to the RIUS-5 was developed more recently by another group [6]. The REP-5 accelerator was designed for electron beams of 3 MeV, 50 kA, and 20 nsec. The intended application of REP-5, however, may be other than production of flash X-rays, since a feature of the design is laser beam initiation of the pulse.

The accelerator is charged by an EG-5 Van de Graaf generator. The high-voltage electrode is 1.6 m in diameter, the line is 3 m long, filled with a gas mixture (25% CO_2 + 75% N_2) at 16 atm. The discharge is initiated by a Q-switched 2.5 J laser. A 50 μ Ti or Al foil serves as anode.

In 1970 Pecherskiy built and tested a flash X-ray machine in which highly purified distilled water was used instead of the gaseous dielectric. This decreased the rate of propagation of the electric field along the line by a factor of 9; a similar decrease was effected in the internal impedance. As a result, the radiation dose could be increased by an order of magnitude in comparison to the earlier machines by shortening the pulse and increasing the current through the tube. The Marx generator under these conditions stored 30 kJ and was rated at 3 MV reached in 0.7 μsec. The electron current amplitude was within the limits of 70 to 120 ka. The X-ray tube produced a radiation dose of 5.10 rads at 1 m from the target with a pulse length of 60 nsec. The fast electron beam can be released into the atmosphere by replacing the anode with a thin titanium or beryllium foil [7].

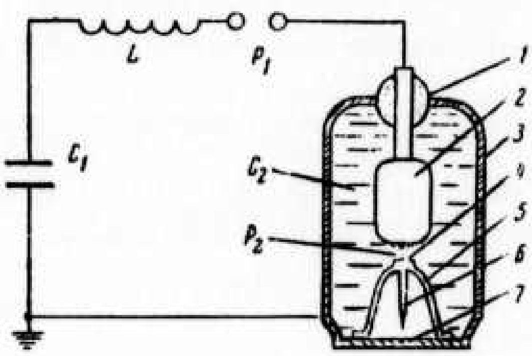


Fig. 4 -- Pecherskiy's flash X-ray machine [5]

C_1 -- Marx generator capacitance; C_2 -- capacitance of water dielectric concentrator; L -- generator inductance; P_1, P_2 -- spark gaps; 1 -- high-voltage input; 2 -- bus; 3 -- cylinder; 4 -- cathode lead; 5 -- accelerator tube; 6 -- cathode; 7 -- anode.

Budker's general interest in the development of flash X-ray machines was directed particularly to the inherent possibilities offered by water as the dielectric medium for the particle accelerator system. On Budker's initiative, Abramyan performed a series of experiments to investigate the properties of specially purified

and distilled water in a RIUS-type machine and to test the effect of pressurization of water [8].

Optimum concentration of energy due to the high permittivity of water (E = 80) and comparatively high breakdown strength (E = 5 x 10^5 kV/cm) makes it possible to employ power levels of the order of 3 x 10^9 W. Other dielectrics such as tranformer oil or polyethylene, used under similar conditions, are said to decrease the power level by approximately two orders of magnitude. Furthermore, water also has the advantage of restoring electric strength after uncontrolled discharges.

Abramyan used a 50-MW pulsed ruby laser in his shadowgraphy of an 0.18-cm spark gap. The results indicated that the development of the prestreamer stage represented essentially the generation of gaseous formations in the local field-amplification region. Although the mechanism of such generation and the role of avalanche processes remained unclear, the work was pursued to pinpoint the key factors to which these phenomena appear most sensitive. The most significant such factor turned out to be external pressure.

Distilled water resistivity of 5 x 10^6 ohm-cm was achieved by deionization, degassing, and filtering to remove mechanical impurities up to 1 μ. The water held in a dielectric chamber with a 3-mm spark gap was compressed up to 140 atm. High voltage was supplied by a 2000-pf 500-kV Marx generator.

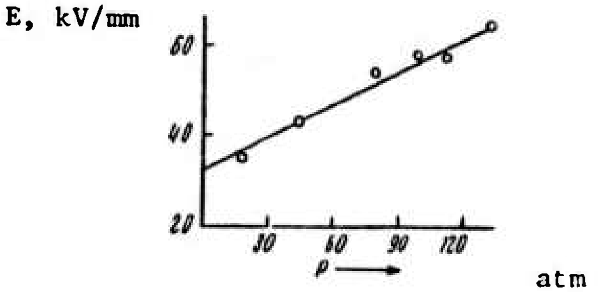


Fig. 5 -- Pressure response of water dielectric [8]

The above plot shows field intensity in the gap below breakdown threshold as a function of pressure applied to the water. It is apparent that breakdown strength of water increases significantly with pressure: An increase from 3 to 140 atm increases electric energy density by an order of magnitude. However, the effect of external pressure is most pronounced in relation to duration of the prestreamer process. Thus, for E = 50 kV/mm at p = 3 atm, τ = 50-100 nsec, while at p = 100 atm, τ = 10-20 μsec. Abramyan regards this dependence as the decisive factor in the successful design of megavolt energy concentrators, since the concentration process can be effective even when driven by low-power primary energy sources.

Using the above results, Abramyan then built a working model of such a concentrator. A closed-cycle water purification system 9 (see Fig. 8) yielded $\rho = 1.8 \times 10^7$ ohm-cm, and a sylphon pressure system provided 100 atm. Energy stored in 5.0×10^{-6}-f 100-kV capacitor bank 1 was transferred to bus 3 by step-up resonance Tesla transformer 2 with a transformation ratio of 21.

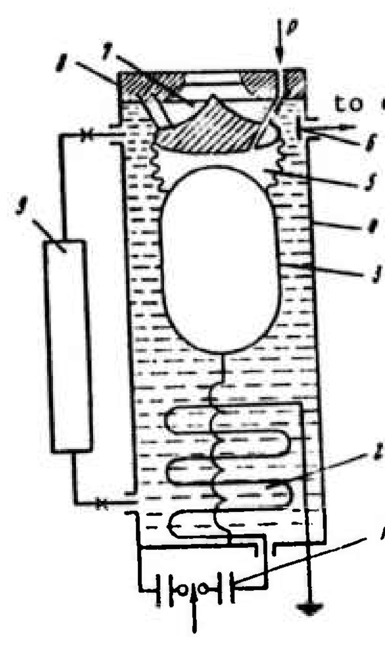


Fig. 6 -- Megavolt energy concentrator for the production of high-power electron beams [8]

5 -- triggered spark gap and sylphon;
6 -- pressure pickup; 7 -- field-emission cathode; 8 -- insulator.

The distance between the internal wall of the housing cylinder 4 and the high-voltage bus 3 is 7 cm. The internal diameter of the cylinder 4 is 56 cm. The machine has a wave impedance of $\sim$ 3 ohms and with a matched load can deliver $\sim 5 \times 10^{11}$ W for a stored energy of $\sim$ 30 kJ. The effect of external pressure can be shown as follows:

At 3 atm, a 3-cm spark gap in water broke down at 0.5×10^6 V, while at 100 atm the same spark gap sustained 2×10^6 V for 6 μsec [8].

The concept of water as a dielectric in fast electron beam machine was further investigated by Pecherskiy [9], who used degassed, purified, and distilled water in an unpressurized state, a 6700-μμf Marx generator, and a voltage range of 0.5 to 1.7 MV. He reported that the breakdown voltage was dependent on pulse length under these conditions. Thus, for a 5-μsec pulse the breakdown field was 300 kV/cm; for pulses of 0.5 μsec it increased to 480 kV/cm. Pecherskiy concluded that, in electric strength, water exposed to short pulses was not inferior to transformer oil.

Similar conclusions were reached by a group of researchers working with L. I. Rudakov on relativistic electron accelerators in fusion applications. In these experiments with purified and degassed water at 5 atm, the electric strength was found to exceed 400 kV/cm for pulses of 0.2 μsec [10]. This principle was incorporated in the "Neptun" accelerator built for 1 MeV, 30 kA, and 40 nsec.

Neptun is driven by two standard GIN-400-0.06/5 voltage generators in series delivering 1.9 kJ to a Blumlein stripline 65 cm long filled with water. The gap switch uses water breakdown for initiation. The pulse shape was found to depend on line impedance; the shortest pulse front was 5-7 nsec for 10-15 Ω lines and average gap field of 1.0-1.5 MV/cm. The water was treated in a special purifier consisting of a TsNG-70 pump, mechanical filters, ion-exchange resin columns, and a degassing vaporizer. The purifier is capable of increasing water resistivity to 6 Mohm.cm in 1.5-2 hours and restoring its dielectric properties after prolonged operation.

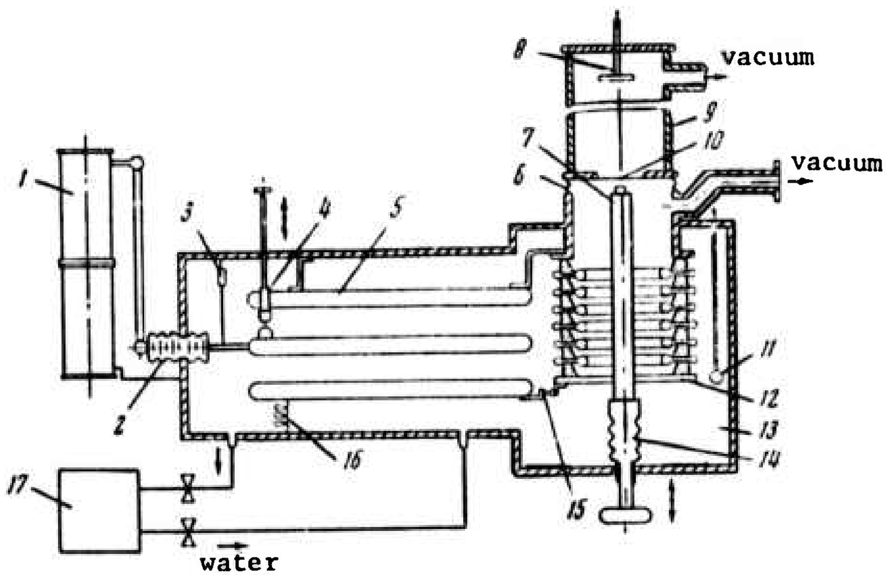


Fig. 7 -- The Neptun accelerator [10]

1 -- GIN-400-0.06/5; 2 -- high-voltage input; 3 -- meter resistor; 4 -- gap switch; 5 -- line strip; 6 -- shunt; 7 -- cathode mounting; 8 -- calorimeter; 9 -- drift tube; 10 -- anode foil; 11 -- capacitive pickup; 12 -- diode; 13 -- tank; 14 -- insulator; 15 -- pulse shaping gap; 16 -- inductor; 17 -- water purifier.

In his review, Tsukerman [1] compared some of the Soviet machines described above with U.S. counterparts. He stated that the most powerful flash X-ray machine appeared to be the Hermes-II developed by Martin, Johnson, and Prestwich of the Sandia Corporation. Martin reported [11] on the Hermes-II as consisting of the Marx generator, a Blumlein transmission line doubling the generator's voltage, and the X-ray tube, placed in a common tank 22 ft. in diameter and 80 ft. long, filled with transformer oil. The parallel-to-series switching of the capacitor bank is accomplished by 93 individually packaged spark gaps. Under these conditions, the dose at 1 m from the target can reach 10^{11} rads/sec.

In 1967 Rex Pay reported [12] that the Physics International Company had commenced the design of a flash X-ray machine capable of producing 50,000 rads at a distance of 1 m from the target in a 100 nsec pulse. To obtain this intensity, which is almost an order higher than that of the Hermes-II, the authors intended to increase the amplitude of the

electron current in the tube to 3 MA for an electron energy of 10 MeV. Tsukerman [1] had no information as to whether this machine had been built or whether these characteristics had been achieved. There is no doubt, however, he stated, that the achievement of such superpower sources of flash X-rays did not involve any difficulties of a basic nature. The use of high permittivity dielectrics and modern technology of high-voltage pulse generation renders the construction of giant generators operating with pulse currents of millions of amperes and accelerating voltages of tens of megavolts quite feasible.

Until recent times the presence of vacuum or low-pressure gas was the necessary condition for the production of X-rays. Thus, all X-ray tubes operated in the left-hand branch of the Paschen curve. However, the excitation of X-rays is, in principle, possible also in the right-hand branch of the Paschen curve, where gas pressures are close to the atmospheric. If the high-voltage pulse has a sufficiently steep slope, discharge in gas occurs at much higher voltages. The field intensity at the cathode becomes sufficient for field emission. Gas ionization and electron emission from the cathode, as a result of cathode bombardment by positive ions, lead to a rapid rise in the number of free electrons in the gap. Under certain conditions, electron energy losses in collisions are lower than the energy acquired by the electrons in deceleration of fast electrons in the gas and in the material of the anode.

According to A. A. Rukhadze of the Lebedev Physics Institute [14], the deceleration of fast electrons converts about 1 percent of their energy into X-rays. Therefore, he expects that 10^{10}-10^{11} W X-ray sources can be obtained with 10^{12}-10^{13} W beams. Rukhadze also considers the possibility of producing X-ray lasers by exposing various gas media to a high-current electron beam with a current density of 10^{7}-10^{8} A/cm^{2}.

Table

CHARACTERISTICS OF HIGH-POWER HARD X-RAY GENERATORS [1]

Country	Author and Device	High Voltage Source	Stored Energy, kJ	Voltage, MV*	Tube Current, ka	Dose per Pulse at 1 m, rads	Pulse Length, nsec	Date	Ref.
U.S.	Denholm, FX-25	Electrostatic	1.7	3.5/2.3	19	2	20	1965	[13]
USSR	Zelenskiy	Marx	200	5/4	50	250	500	1967	[3]
USSR	Abramyan, RIUS-5	Tesla transformer	5.4	7/4	15	10	40	1969	[4]
U.S.	Martin, Hermes-II	Marx	1000	24/13	200	6800	70	1969	[11]
USSR	Pecherskiy	Marx with H_2O dielectric	30	3/1.5	100	10	60	1970	[7]

*Numerator of the fraction indicates bus voltage, denominator indicates accelerator tube voltage.

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